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Improving Building Envelope and Duct Airtightness of US Dwellings – The Current State of Energy Retrofits

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ABSTRACT

We analyzed the building envelope and duct system airtightness of US single-family detached homes, manufactured homes, and multi-family homes, before and after energy retrofits. These data are part of the Residential Diagnostics Database (ResDB) by Lawrence Berkeley National Laboratory. Weatherization Assistance Program (WAP) contributed 21,140 paired blower door measurements of building envelope air leakage, and residential energy efficiency programs contributed another 10,000 paired measurements. Eighteen states are represented. There are fewer duct blaster measurements to characterize the air leakage of duct systems. Pre- and post-retrofit measurements are available from only 460 homes located in California and Nevada. The median improvement in building envelope airtightness from energy retrofits is 20% to 35% for several groups of homes considered. The levels of improvement varied slightly from state to state, and also between program types. Larger improvements were observed among WAP homes, and in particular those that were very leaky before the energy retrofit. In contrast, the duct leakage data show improvements that varied substantially by program. Based on total duct leakage data from California only, non-WAP homes that were retrofitted by energy efficiency programs showed a median reduction in duct leakage of 75%. Contrarily, WAP homes only showed a 25% improvement. This is evident of some of the programmatic differences that influenced the retrofit outcomes. Estimates of airtightness improvements are useful for calculating the energy savings and cost-benefit ratio of air sealing as a way to improve the energy efficiency in US homes. This analysis shows that there is a small fraction of retrofitted homes by energy efficiency programs that have post-retrofit airtightness exceeding 15 ACH50 for building envelope, and 12 CFM25 (per 100 ft^2 of conditioned floor area) for duct leakage. These leakage values are far higher than levels that are considered as acceptable airtightness even for existing homes, thus shows that there are opportunities to increase the energy saving potential of energy retrofit programs if these inadequacies can be addressed.

KEYWORDS

Blower door; duct blaster; fan pressurization test; weatherization; energy efficiency

1. INTRODUCTION

Airtightness testing of building envelope and duct system are frequently performed in homes to show the improvements resulted from energy efficiency retrofits. The Weatherization Assistance Program (WAP) under the American Reinvestment and Recovery Act (ARRA) of 2009 had led to a large number of building envelope and duct system airtightness tests before and after retrofits. Between 2002 and 2007, the average number of income-qualified homes weatherized per year was about 100,000 (DOE 2010a). Under ARRA as of November 2011, over 600,000 homes were weatherized in less than two years (DOE 2010b). In addition, many states have utility sponsored energy efficiency programs that give their customers incentives to preform home energy upgrades. In many cases, such programs follow the Home Performance with ENERGY STAR (HPwES) guidelines. HPwES is implemented in over thirty states in the US. Since its launch in 2001, 200,000 homes had performed energy upgrades under HPwES (EPA 2012).

There are significant differences between WAP and HPwES type of energy efficiency programs in terms of funding sources, eligibility criteria, target households, etc. But common to all energy retrofits are some measures that aim to reduce air leakage, including weatherstripping and air sealing of joints, seams, penetrations, attic openings, and rim joints

(Baechler and Love, 2010). Polly et al. (2011) evaluated a variety of energy efficiency options and predicted their energy saving potentials for the US housing stock by climate zones. Their evaluations are based on the modeling assumptions that energy efficiency measures can reduce the whole-building envelope air leakage by half, from 19 ACH50 to 10 ACH50. Polly et al. (2011) referenced the HPwES website (EPA, 2013), where the 55% reduction post-retrofit is calculated from an assumption that "homes were estimated to be improved to a leakage level of 0.50 ACHNAT" (natural air changes per hour). Prior to improvement, EPA (2013) assumed an average value of 0.91 ACHNAT for Northern homes, and 0.94 ACHNAT for Southern homes.

Furthermore, Polly et al. (2011) assumed that duct sealing can also reduce duct leakage to-outside by half from 15% of the total fan flow to 8%. The 50% reduction in duct leakage to-outside is based on a study by Francisco et al. (1998). Citing other field studies where the reduction in duct leakage is less, Polly et al. (2011) described the 50% modeled as "possible but could be toward the upper range of what is commonly achieved in the field".

There are many factors that can impact the level of airtightness improvements achieved from retrofit, such as the existing condition of the home, available time and budget to do the work, workmanship, and so on. Therefore, to evaluate the airtightness improvements from retrofits commonly achieved in the US would require a large dataset that include the before and after retrofit measurements from various types of programs. The Residential Diagnostics Database (ResDB) by Lawrence Berkeley National Laboratory contains air leakage and other diagnostic measurements of US homes that are contributed voluntarily by various energy auditors, building contractors, energy efficiency program managers, and researchers (Chan et al. 2012). In this paper, we compared the whole-building envelope and duct system air leakage before and after retrofits using the data available from ResDB.

2. RESDB AIR LEAKAGE MEASUREMENTS

In 2011, a large number of whole-building envelope air leakage data from more than 100,000 homes were added to ResDB. Chan et al. (2012) described the air leakage data of single-family homes, and presented a regression model that relates normalized leakage (NL) to house characteristics, such as climate zone, year built, floor area, and so on. Over the years, air leakage data have been gathered and analyzed to support calculations of air infiltration and implications to residential energy use (e.g., McWilliams and Jung 2006, Chan et al. 2005, Sherman and Matson 2001, Sherman and Dickerhoff 1998).

This analysis only considers a subset of the data in ResDB where air leakage measurements were made before and after retrofit. Two types of programs contributed these data: (i) WAP and (ii) energy efficiency programs, often sponsored by utilities and many of them follow HPwES guidelines. There is one exception to the data considered as part of (ii), where the homes being tightened participated in a noise reduction program (Bohac and Cheple 2002). This particular program is also included in this analysis because the types of improvements performed, e.g., air sealing and insulation, were largely the same as those taken for by energy retrofit. Overall, (i) includes 13 WAP, and (ii) includes ten energy efficiency programs and also data from the noise reduction program. All together, air leakage data of US homes from 18 states are considered.

Most of this analysis focuses on single-family detached homes, which is the dominant type of housing in the US. A subset of single-family homes are manufactured homes, sometimes referred as mobile homes. Manufactured homes are considered as a separate group because their construction is substantially different from conventional homes. In the US, manufactured homes are built to the Manufacture Home Construction and Safety Standards set by the Department of Housing and Urban Development (HUD 2013). This is unlike other housing types that are built to state building codes. In addition, the WAP data also include a small number of multi-family units. Because few data on multi-family units are available, the various types (e.g., townhouse, apartments, etc.) are considered in this analysis as a single group. This is a simplification in our approach, because there may be large differences in the air leakage pathways of different types of multi-family buildings that is not considered in this analysis. All data on manufactured and multi-family homes are contributed by WAP.

2.1. Blower door measurements

ASTM Standard E779-10 (ASTM 2010) is the measurement standard used in the US to measure building envelope air leakage. Air leakage is measured by the airflow rate, Q (m^3/s) through the building envelope as a function of the pressure difference, ΔP (Pa), across the building envelope. The most common pressure difference used is 50 Pa, which is low enough for standard blower doors to achieve in most houses, and at the same time high enough to be reasonably independent of weather influences. Many metrics are used to describe whole-building envelope air leakage normalized to building volume or some definitions of surface area, such as ACH50 (air changes at 50 Pa pressure difference), NL (normalized leakage), ELA (effective leakage area), SLA (specific leakage area), and so on. There is no consensus from retrofit guidelines or buildings codes on which one metric is preferable to the others. ACH50 is used as the metric to describe the improvement in airtightness from retrofit in this analysis as follows:

$$\%\ \text{Reduction} = \left(1 - \frac{\text{ACH50}_{\text{post}}}{\text{ACH50}_{\text{pre}}}\right) \times 100\% \qquad (1)$$

2.2. Duct blaster measurements

Duct leakage is commonly measured following ASTM Standard E-1554 (ASTM 2007), where a calibrated fan is used to pressurize the duct system with all registers closed. For measuring duct leakage, 25 Pa is commonly used to represent a pressure difference that resembles typical conditions during system operation. Among the many different metrics used to describe duct system air leakage, one that is commonly used in the US is CFM25 (cubic foot of air flow per minute at 25 Pa) normalized to per 100 ft^2 of conditioned floor area. This is the metric used here to compare the airtightness improvement before and after duct sealing. Most of the data in ResDB are total duct leakage, $Q_{duct,\ total}$, that includes air leakage to outside as well as to other parts of the building. In addition, there are a small number of homes where duct leakage to-outside was measured by pressurizing the house simultaneously with a blower door to the same pressure as the duct system during the test. The duct leakage to-outside, $Q_{duct,\ to\text{-}outside}$, is the flow required to equalize the house and duct pressures.

3. WHOLE-BUILDING ENVELOPE AIRTIGHTNESS IMPROVEMENTS

3.1. Data Analysis

The pre- and post-retrofit whole-building envelope airtightness measurements are shown in Figure 1. There are clear improvements across all programs and housing types. Comparing the non-WAP energy retrofit and WAP single-family detached homes, the improvements made by WAP tend to be slightly larger, as shown in Table 1. This may be because it is easier to achieve a large improvement in airtightness if the homes were more leaky to begin with. Among these WAP single-family detached homes, there is a positive correlation between $ACH50_{pre}$ and the percentage reduction: Pearson correlation coefficient $r = 0.399$ (95% confidence interval: 0.385–0.413). The correlation is also positive among non-WAP energy retrofit homes ($r = 0.132$, 95% C.I.: 0.113–0.151), but the relationship is far weaker. This is likely because there were fewer non-WAP energy retrofit homes with very high initial ACH50 where the opportunities for substantial improvements were possible.

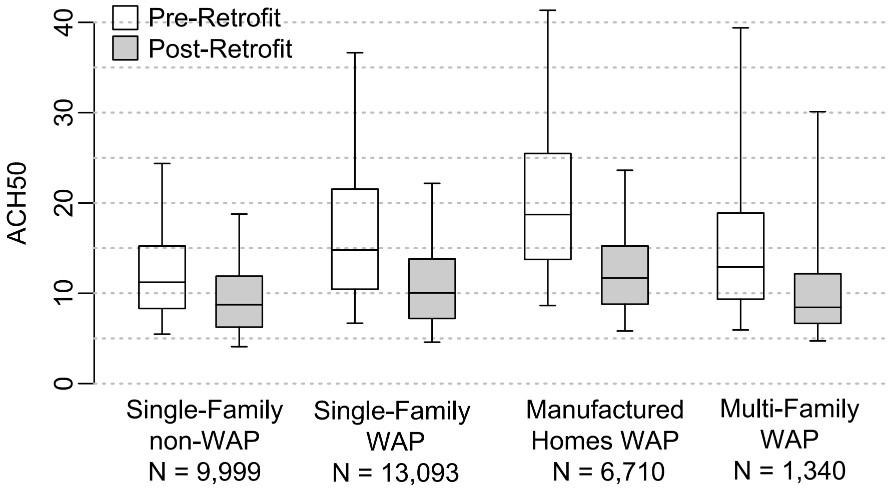

Figure 1: Whole-building envelope airtightness, in units of ACH50, of US homes measured before and after energy retrofit. Each boxplot shows the median and interquartile range, and the whiskers show 5th and 95th percentiles. N = number of homes.

Table 1: Percentage reduction in whole-building envelope air leakage (ACH50) following retrofit.

	non-WAP	Weatherization Assistance Program (WAP)		
	Single-Family Detached Homes	Single-Family Detached Homes	Manufactured Homes	Multi-Family Homes
Median	20%	30%	35%	28%
5th to 95th Percentiles	5% to 47%	5% to 61%	9% to 64%	3% to 59%

Among the WAP homes, manufactured homes have higher ACH50 than the single-family detached homes, but the multi-family homes have lower ACH50. This is true both in the pre- and post-retrofit data. These three housing types are very different in characteristics that may contribute to this apparent variance in airtightness. For example, the median floor area of manufactured homes in ResDB is 93 m^2, which is smaller than both the single-family detached homes (median = 132 m^2) and the multi-family homes (median = 129 m^2). Since floor area is one of the housing characteristics found to be negatively associated with air leakage (Chan et al. 2012), the manufactured homes being smaller in floor area may explain the higher in ACH50 overall. In addition, climate zone and year built are two factors that the regression analysis identified as the most influential on normalized leakage (Chan et al. 2012). Unfortunately, the differences among climate zones cannot be properly accounted for because only a small number of states are represented (see Figure 2). There are also too many missing data to compare the year built of homes among the three housing types.

The ACH50 measurements of multi-family homes included both the air leakages to outside and to adjacent units. The majority of WAP contractors used this whole-unit approach because it is the least time consuming to perform. On the other hand, if the purpose is to determine the to-outside air leakage only, multiple blower doors are needed to simultaneously pressurize the adjacent units. This is not only more labor intensive to do, but it is also logistically demanding because it requires access to multiple housing units for testing. Therefore, the improvement in airtightness shown in Table 1 cannot be used directly to estimate energy savings. Rather, it reflects an improvement in compartmentalization, where the reduction in inter-unit air flows also benefits occupant health and comfort, besides energy savings.

3.2. Implications

The modeling assumption by Polly et al. (2011), i.e., 50% reduction from 19 ACH50 to 10 ACH50, is overly optimistic for a vast number of US homes based on data from ResDB. WAP and energy efficiency programs typically improved airtightness by 20% to 35% (Table 1) across all housing types. This analysis shows that there are opportunities for further improvements. The first is the large scattering in the percentage reduction across many of these retrofit programs, where some homes received marginal improvements in airtightness. Approximately 16% of the non-WAP energy retrofitted single-family detached homes had marginal improvements (<10% reduction in ACH50). Because WAP require contractors to repeat the blower door measurements multiple times during retrofit to check if a reduction has been made, there are fewer cases of marginal improvements: 6% in manufactured homes, 12% in single-family detached homes, and 16% in multi-family homes.

The second issue is the large fraction of homes that continue to have poor airtightness even after the energy retrofit. Most retrofit programs in the US do not set a target for improvement in airtightness, but rather recommend best-practice approaches for contractors to follow, such as HPwES (EPA, 2012). Table 2 shows that in a significant portion the homes, ranging from 36% to 64% depending on the housing type, exceed 10 ACH50 after energy retrofits.

Table 2: Percentage of homes with post-retrofit envelope air leakage exceeding two levels: 10 and 15 ACH50.

	non-WAP	Weatherization Assistance Programs (WAP)		
	Single-Family Detached Homes	Single-Family Detached Homes	Manufactured Homes	Multi-Family Homes
$ACH50_{post} > 10$	39%	50%	64%	36%
$ACH50_{post} > 15$	12%	20%	26%	18%

Figure 2 shows the % reduction in ACH50 by states. There are substantial within-state differences, where the coefficient of variance, i.e. standard deviation divided by mean, is about 0.5. In addition, Figure 2 also shows that there are between-state differences. For example, the % reduction in ACH50 from WAP homes in California and Arkansas appeared to be very different from the other states. Using boxplot as a tool to identify possible outliers, WAP homes from these two states are extreme outliers, but not in the case of non-WAP single family homes. If these outlier sets of data are excluded, the remaining states show similar % reduction in ACH50 among the WAP homes. The median % reduction ranges from 25% in Washington to 35% in Virginia, for the single family WAP homes. For the non-WAP single family homes, the median % reduction ranges from 18% in New Jersey to 39% in Nevada. From this viewpoint, there is a larger difference between states among the non-WAP homes (39% - 18% = 21%) than the WAP homes (35% - 25% = 10%).

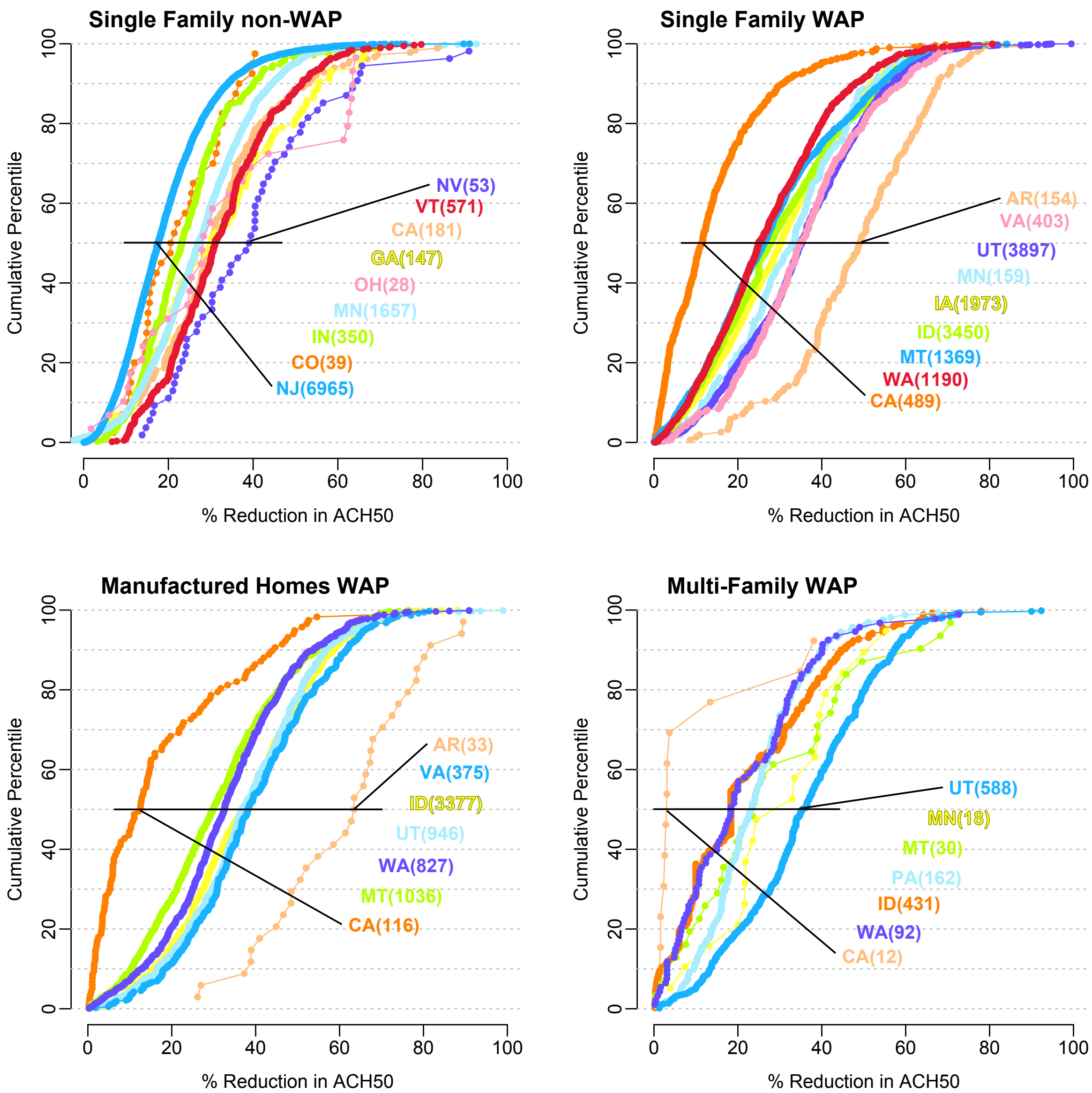

Figure 2: Percentage reduction in whole-building envelope air leakage (ACH50) following energy retrofit. Data from each of the states are color-coded and ordered to give the cumulative percentile on the y-axis.

Data from the WAP manufactured homes (Figure 2) also show relatively small between-state differences, in comparison to the within-state differences. In contrast, the multi-family WAP homes are more variable between states. But because of the small dataset, this is a preliminary observation.

One plausible reason to explain why the WAP data are more similar between states is because there is more common ground among the participating homes, where all households are qualified by their income. In comparison, the housing characteristics of non-WAP participants are likely to be more diverse. Differences in program incentives can also play a role. For example, many homes in California are located in moderate climates where the energy penalty of air leakage is less severe than homes located in colder climates. This explains the modest reduction in ACH50 relative to the other states.

4. DUCT SYSTEM AIRTIGHTNESS IMPROVEMENTS

4.1. Data Analysis

ResDB only contains a small amount of duct leakage data from California and Nevada that show reduction due to retrofit. This lack of data is because initially, the ResDB data collection effort focused more heavily on whole-building envelope airtightness data than on duct leakage. Figure 3 compares the before and after duct leakage data from the 460 homes. Before retrofit, the median $Q_{duct,\ total}$ was 27 CFM25 for the non-WAP single-family detached homes in California. The pre-retrofit duct leakage is roughly the same among the WAP single-family detached and manufacture homes in California, where the median $Q_{duct,\ total}$ are 22 and 29 CFM25, respectively. However, there are stark differences in the improvements made by the retrofits. The median reduction for non-WAP after retrofit is 75% (Table 3). Whereas in the case of WAP, the median reduction is 23% among the single-family detached homes, and 28% in the manufactured homes. This vast difference between the two program types is likely because weatherization contractors tend to use relatively simple measures to reduce obvious leakage in the duct systems. On the other hand, energy efficiency programs, with more flexibility in work scope and budget, are more likely to recommend heating and cooling equipment upgrades, and thus trigger an inspection and overhaul of the duct systems. Moreover, identifying duct leakage is a relatively time-consuming and labor-intensive process, which makes duct sealing less favorable when evaluated on a savings-to-investment ratio for WAP.

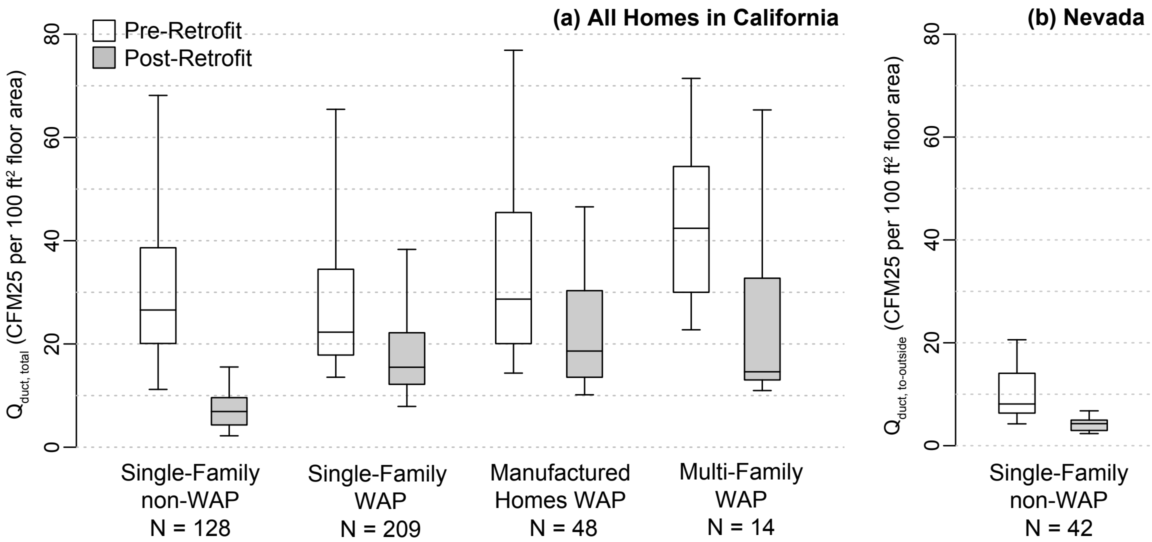

Figure 3: Duct leakage of California and Nevada homes measured before and after energy retrofit. The California data (a) are total duct leakage, whereas the Nevada data (b) are duct leakage to-outside. Each boxplot shows the median and interquartile range, and the whiskers show 5th and 95th percentiles. N = number of homes.

The multi-family measurements shown in Figure 3 were likely performed on the duct systems that were present within each unit. Typically, this is a prerequisite for compliance testing in multi-family homes; for example, see RESNET draft standards on air leakage testing (2013). From this small dataset of only 14 homes, it appears that duct leakage is a problem in multi-family homes at a level that is comparable to the WAP single-family homes. Proctor et al. (2011) compared the duct leakage of newly constructed single-family and multi-family homes in California and found relatively higher duct leakage among the multi-family homes. However, the same value of $Q_{duct,\ total}$ can have vastly different energy implications depending on the location of the ducts (e.g., inside versus outside of the conditioned space), sizing of the heating and cooling equipment, and so on. Unfortunately, there is insufficient data on duct leakage from ResDB to support a more detailed analysis of the energy implications at this point.

Table 3: Percentage reduction in total duct system air leakage (CFM25 per 100 ft^2 floor area) following retrofit.

	non-WAP	Weatherization Assistance Program (WAP)		
	Single-Family Detached Homes	Single-Family Detached Homes	Manufactured Homes	Multi-Family Homes
Median	75%	23%	28%	46%
5th to 95th Percentiles	43% to 93%	4% to 72%	6% to 66%	2% to 72%

Measurements from an energy efficiency program in Nevada provide data on the change in duct leakage to-outside before and after retrofit. The change in $Q_{duct, to-outside}$ has a median value of 49% (5th to 95th percentiles = 11% to 80%), which is the same as the level of reduction (50%) assumed by Polly et al. (2011) in their modeling work.

4.2. Implications

The duct system airtightness of non-WAP homes following energy retrofits is sufficient to meet levels that are expected of new homes. For example, the IECC (2009) requirement was ≤12 CFM25 (per 100 ft^2 of conditioned floor area) for total duct leakage, and ≤8 CFM25 for duct leakage to-outside. Figure 3 shows that majority of the non-WAP homes retrofitted in California (85%) and in Nevada (98%) met those airtightness levels. On the other hand, relatively few WAP homes would meet IECC (2009): 23% of single-family detached homes, 13% of the manufactured homes, and 15% of the multi-family homes (Table 4). Recall that WAP homes also had higher pre-retrofit building envelope air leakage than the non-WAP homes (Figure 1); this is the same as the case for duct leakage. However, opposite of the case for building envelope leakage, WAP improved the duct leakage of homes by a lesser extent overall than the energy efficiency programs. Contrasting these two cases, it is evident how incentives can drive the level of airtightness improvements in energy retrofits.

Table 4: Percentage of homes with post-retrofit total duct leakage exceeding IECC (2009) levels: 8 and 12 CFM25 per 100 ft^2 floor area.

	non-WAP	Weatherization Assistance Programs (WAP)		
	Single-Family Detached Homes	Single-Family Detached Homes	Manufactured Homes	Multi-Family Homes
$CFM25_{post} > 8$	39%	95%	96%	100%
$CFM25_{post} > 12$	15%	77%	87%	85%

In their evaluation of energy efficiency measures, Polly et al. (2011) assumed that duct system air leakage to-outside would be reduced by half from 15% of the total fan flow to 8%. The energy efficiency programs in California reduced total duct leakage by 75%, and in Nevada by 50% on the duct leakage to-outside. These airtightness improvements are on par with the modeling assumptions by Polly et al. (2011). On the other hand, WAP, at least among those in California, where the data is available from ResDB, achieved much less improvement in duct system airtightness than the 50% modeled by Polly et al. (2011). The conversion from CFM25 (per 100 ft^2 of conditioned floor area) to duct leakage as a percentage of fan flow depends on many factors. If applying common assumptions of 400 CFM per ton of air conditioning and 400 ft^2 per ton, then roughly speaking, 8 CFM25 per 100 ft^2 of conditioned floor area is simply 8% of fan flow. Using this rough conversion, almost all of the single-family detached homes in Nevada have duct leakage to-outside <8% of fan flow post-retrofit.

5. CONCLUSIONS

We analyzed the building envelope and duct system airtightness of US single-family detached homes, manufactured homes, and multi-family homes, where the data was part of the Residential Diagnostics Database (ResDB). The data in ResDB were mostly contributed by Weatherization Assistance Program (WAP) and residential energy efficiency programs. The analysis here shows that these programs typically reduced building envelope air leakage by 20 to 35% (median reduction in ACH50, N = 31,140). The reduction in building envelope air leakage post-retrofit was slightly higher among WAP, for reasons that may be associated with how weatherization contractors are required to check for improvements for each increment of work. Greater improvements are also correlated with the higher initial ACH50 found among the income-qualified homes that participated in WAP.

It is more difficult to draw conclusion from the duct leakage retrofit comparison because far fewer data (N = 460) are available from ResDB to compare duct system leakage before and after retrofit. From the limited data available in California, single-family detached homes retrofitted by energy efficiency programs showed a reduction in total duct leakage (CFM25 per 100 ft^2 of conditioned floor area) of 75%. Such improvements are significantly greater than the WAP homes, where CFM25 was reduced by roughly 25%. In Nevada, the median reduction in duct leakage to-outside was 50%, estimated from a small set of single-family detached homes retrofitted by an energy efficiency program. The larger reductions observed from these two energy efficiency programs mentioned suggest that given the resources to overhaul the duct systems, which may be cost prohibitive for WAP, duct leakage can be effectively minimized in existing homes.

The air leakage reductions presented here are useful for calculating the expected energy savings and cost-benefit ratio of air sealing as a way to improve energy efficiency in US homes. This analysis also identified opportunities for retrofit programs to enhance their energy saving potentials. Homes with minimal improvements (e.g., less than 10% reduction in ACH50), and those that ended with relatively high post-retrofit air leakage (e.g., >15 ACH50), should prompt further investigation. Once an acceptable set of thresholds is established as a target, retrofit programs should implement procedures that will provide incentives for a follow-up visit. They should also ensure that the recommendations from best practice guides on air sealing (e.g., Baechler and Love (2010)) are fully utilized by contractors in energy retrofits.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

ASTM. 2007. *Standard Test Methods for Determining Air Leakage of Air Distribution Systems by Fan Pressurization E1554.* American Society for Testing and Materials, Washington, DC.

ASTM. 2010. *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization.* American Society for Testing and Materials, Washington, DC.

Baechler, M.C., and P.M. Love. 2010. *Retrofit Techniques and Technologies: Air Sealing, a Guide for Contractors to Share with Homeowners.* Report prepared for US Department of Energy, PNNL Report 19284.

Bohac, D., and M. Cheple. 2002. Ventilation and Depressurization Information for Houses Undergoing Remodeling. Final Report prepared for Minnesota Department of Commerce, State Energy Office.

Chan, W.R., W.W. Nazaroff, P.N. Price, M.D. Sohn, and A.J. Gadgil. 2005. Analyzing a database of residential air leakage in the United States. *Atmospheric Environment* 39(19), 3445-3455.

Chan, W.R., J. Joh, and M.H. Sherman. 2012. *Analysis of Air Leakage Measurements from Residential Diagnostics Database*. Lawrence Berkeley National Laboratory, LBNL Report 5967E, Berkeley, CA.

DOE. 2012a. Weatherization Assistance Program Goals and Metrics. Weatherization and Intergovernment Program, US Department of Energy, Washington, DC. http://www1.eere.energy.gov/wip/wap_goals.html. Accessed 2012/12/05.

DOE. 2012b. ARRA Homes Weatherized by Grantee. US Department of Energy, Washington, DC. http://energy.gov/downloads/arra-homes-weatherized-grantee. Accessed 2012/12/05.

EPA. 2012. Home Improvement: Improve Your Home's Energy Efficiency with ENERGY STAR. US Environmental Protection Agency, Washington, DC. http://www.energystar.gov/index.cfm?c=home_improvement.hm_improvement_index . Accessed 2012/12/05.

EPA. 2013. Methodology for Estimating Energy Savings from Cost-Effective Air Sealing and Insulating. US Environmental Protection Agency, Washington, DC. http://www.energystar.gov/index.cfm?c=home_sealing.hm_improvement_methodolog y. Accessed 2013/03/12.

Francisco, P.W., L. Palmiter, and B. Davis. 1998. Modeling the thermal distribution efficiency of ducts: comparisons to measured results. *Energy and Buildings*, 28, 287-297.

HUD. 2013. *Manufactured Home Construction and Safety Standards.* US Department of Housing and Urban Development, Washington, DC. http://portal.hud.gov/hudportal/HUD?src=/program_offices/housing/ramh/mhs/mhcss. Accessed 2013/03/11.

IECC. 2009. *International Energy Conservation Code*. International Code Council, Washington, DC.

McWilliams, J., and M. Jung. 2006. *Development of a Mathematical Air-Leakage Model from Measured Data.* Lawrence Berkeley National Laboratory, LBNL Report 59041, Berkeley, CA.

Polly, B., M. Gestwick, M. Bianchi, R. Anderson, S. Horowitz, C. Christensen, and R. Judkoff. 2011. *Method for Determining Optimal Residential Energy Efficiency Retrofit Packages*. Report prepared for Building America, Building Technologies Program, Office of Energy Efficiency and Renewable Energy, US Department of Energy, NREL Report TP-5500-50572.

Proctor, J., R. Chitwood, and B.A. Wilcox. 2011. *Efficiency Characteristics and Opportunities for New California Homes.* Final Project Report. Prepared for California Energy Commission. Publication No. CEC-500-2012-062, Sacramento, CA.

RESNET Standards. 2012. Chapter Eight on Air Leakage Testing (draft July 22). http://www.resnet.us/standards/DRAFT_Chapter_8_July_22.pdf. Accessed 2013/03/11.

Sherman, M.H., and D.J. Dickerhoff. 1998. Airtightness of US dwellings. *ASHRAE Transactions*, 104(2), 1359-1367.

Sherman, M.H., and N.E. Matson. 2001. Air tightness of new houses in the U.S. *Proceedings of 22nd Air Infiltration and Ventilation Center*, Bath, UK, September 11-14.